Flavor mixed sleptons and its consequences at 1-loop level

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Abstract. In this work we explore a lepton flavor violation effect induced at one loop for a flavor structure in an extended minimal standard supersymmetric model, considering an ansatz for the trilinear term of the soft supersymmetric Lagrangian. In particular we find a finite expression for $\tau \to \mu\gamma$ and $h \to \mu\tau$ decay, produced by flavor mixed sleptons running in the loop.

1. Introduction

In the Standard Model (SM) lepton flavor violation processes were forbidden by the lepton number conservation, which is not associated with a gauge symmetry. In the SM, the spontaneous breaking of the electroweak symmetry produces eigenstates of the remaining gauge group that are not in general eigenstates of the mass matrix [1–4]. But after diagonalization of the mass matrix, the electroweak coupling matrix is also diagonal in the mass basis, therefore there is no possibility for lepton flavor violation. Nevertheless, this symmetry is lost in neutrino oscillation found in experiments [5–8], which forces the model structure to go beyond the SM.

This lost symmetry on leptons observed in the neutrino mixing evidence opens also the possibility of lepton flavor violation in the charged sector. The original structure of the SM with massless, and thus degenerate neutrinos, implied separately τ, μ, e number conservation. In particular, the processes $\tau^{\pm} \to l^{\pm}\gamma, (l = \mu^{\pm}, e^{\pm})$ through gauge bosons loops are predicted to give$*$ very low rates [9] Experimental data taken from CMS at 8 TeV with $19.7 fb^{-1}$ had shown an excess for $BR(h^0 \to \tau\mu)$ of 2.4σ with best fit branching fraction of $0.84^{+0.39}_{-0.37}\%$ [10]. Nevertheless data from ATLAS has shown only a 1σ significance for the same process [11]. Moreover, also recent measurements at 13 TeV, although with only $2.3 fb^{-1}$ of data, has shown no evidence of excess. It was even reported [12] a best fit branching fraction of -0.56%. The sign change may imply a statistical error of the data. Even for those latest reports, if they are confirmed, they will indicate a very low range for this lepton flavor violation processes to occur at these energies. These will set stringent bounds to any model beyond the SM. One of the works toward this direction is done in [13], where it has been explored it in a Two Higgs Doublet Model with flavor violation in the Yukawa couplings, a model known as THDM-III [14]. In order to fit these restrictions bounds, the model we proposed in this work of a scalar flavor extended MSSM, should show exclusions regions in the parameter space.

The most recent data by the LHC at 13 TeV have not shown evidence for supersymmetry for different channels and observables as events with one lepton as final state [12], jets and leptons or three leptons [15], missing energy [16]. The experimental search is mainly for the Lightest Supersymmetric Particle (LSP) as missing energy, these reports analyses the data for simplified

$*$A maximal mixing and a value of $\Delta^2_{32} \approx 3 \times 10^{-3}(eV/c^2)^2$ gives $\mathcal{B}(\tau \to \mu\gamma) \approx \mathcal{O}(10^{-54})$

supersymmetric models at this specific energy. The results of these analysis have reduced the parameter space for Minimal Supersymmetric Standard Model (MSSM). Nevertheless we claim that is important to fully explore the possible parameter space for different non-simple supersymmetric low energy models knowing that Supersymmetry still solves many phenomenological issues [17, 18] and also is needed for many GUT models. A review on flavor violation processes in the MSSM considering neutrino mixing can be found in [19]. In this work we implement a flavour structure which implies flavour violation and non-universality of sfermions, this was previously introduced in [20] and was used also in a similar work in [21].

2. Flavor mixed sleptons

As the evidence on flavor violation in charged lepton is not yet conclusive but gives low values for these branching ratios, one possibility is to have a mixed flavor structure in an unseen sector as the sfermions, and then this mixing will induce flavor violation through radiative corrections.
In the case of sfermions, as they are scalar particles, the L, R are just labels which identify to their fermionic SM partners, but they no longer have left and right $SU(2)$ properties. In general they may mix in two physical states.

$$\begin{aligned} \mu_L &\longrightarrow \tilde{\mu}_1 \\ \mu_R &\longrightarrow \tilde{\mu}_2 \\ \tau_L &\longrightarrow \tilde{\tau}_1 \\ \tau_L &\longrightarrow \tilde{\tau}_2 \end{aligned} \tag{1}$$

The mixing of slepton states will be given by a flavor structure in the mass matrix, these have been studied before from different sources of Fv in the scalar sector and with different methods as is discussed in [22] (see dthe references therein); specifically we explore the possibility of having mixing flavor terms in the trilinear couplings of the soft supersymmetric Lagrangian.

$$\mathcal{L}^{f}_{soft} = -\sum_{\tilde{f}_i} \tilde{M}^2_{\tilde{f}} \tilde{\bar{f}}_i \tilde{f}_i - (A_{\tilde{f},i} \tilde{\bar{f}}^i_L H_1 \tilde{f}_R{}^i + h.c), \tag{2}$$

where $\tilde{f}$ are the scalar fields in the supermultiplet. Once the EW symmetry breaking is considered, the trilinear term of the soft SUSY Lagrangian for the sleptonic sector takes the following form

$$\mathcal{L}_{H\tilde{f}_i\tilde{f}_j} = \frac{A^{ij}_l}{\sqrt{2}} \left[(\phi^0_1 - i\chi^0_1)\tilde{l}^*_{iR}\tilde{l}_{jL} - \sqrt{2}\phi^-_1 \tilde{l}^*_{iR}\tilde{\nu}_{jL} + v_1 \tilde{l}^*_R \tilde{l}_L \right] + h.c.$$

We can see, from the flavor non-minimal structure of the trilinear terms of the soft breaking Lagrangian, that we would have FV couplings in charged sleptons, but also with sleptons and sneutrinos via the charged Higgs boson, and the last term implies an extra contribution also to the mass of the sleptons. The contribution to the elements of the sfermion mass matrix come from the interaction of the Higgs scalars with the sfermions, which appear in different terms of the superpotential and soft-SUSY breaking terms as is fully explained in [23, 24]. We work on a model which considers flavor violation between two families in the trilinear scalar couplings. This would give rise to a 4×4 matrix, diagonalizable through a unitary matrix $Z_{\tilde{l}}$, such that $Z^\dagger_{\tilde{l}} \tilde{M}^2_l Z_{\tilde{l}} = \tilde{M}^2_{diag}$. For the complete and explicit development of the mixing flavor slepton model we refer to [22]. From those results we calculate the amplitud matrices for the different processes we analyze here.

We will have then physical non-degenerate slepton masses as given in [22]

$$m^2_{\tilde{l}_{1,2,3,4}} = \frac{1}{2}(2\tilde{m}^2_S \pm X_m - X_t \pm R), \tag{3}$$

where $R = \sqrt{4A_y^2 + (X_t - X_m)^2}$ with $A_y = \frac{1}{\sqrt{2}} y A_0 v \cos\beta$, $X_m = \frac{1}{\sqrt{2}} w A_0 v \cos\beta - \mu_{susy} m_\mu \tan\beta$ and $X_t = \frac{1}{\sqrt{2}} A_0 v \cos\beta - \mu m_\tau \tan\beta$.
We may write the transformation which diagonalizes the mass matrix as a 4×4 rotation matrix for sleptons $Z_{\tilde{l}}$, which is in turn a 2×2 block matrix $Z_{\tilde{l}}^\dagger \tilde{M}_{\mu-\tau}^2 Z_{\tilde{l}} = \tilde{M}_{l,diag}^2$, explicitly having the form

$$Z_{\tilde{l}} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi & -\Phi \\ \Phi\sigma^3 & \Phi\sigma^3 \end{pmatrix} , \tag{4}$$

where σ_3 is the Pauli matrix and

$$\Phi = \begin{pmatrix} -\sin\frac{\varphi}{2} & -\cos\frac{\varphi}{2} \\ \cos\frac{\varphi}{2} & -\sin\frac{\varphi}{2} \end{pmatrix}, \quad \tan\varphi = \frac{2A_y}{X_m - X_t}, \tag{5}$$

The non-physical states are transformed to the physical mixed flavor eigenstates as

$$Z_{\tilde{l}}^\dagger \begin{pmatrix} \tilde{\mu}_L \\ \tilde{\tau}_L \\ \tilde{\mu}_R \\ \tilde{\tau}_R \end{pmatrix} = \begin{pmatrix} \tilde{l}_1 \\ \tilde{l}_2 \\ \tilde{l}_3 \\ \tilde{l}_4 \end{pmatrix} \tag{6}$$

3. One-loop flavour violation processes within muons and taus

In this section we show three processes on which slepton mixing flavor loops contribute. We calculate $BR(\tau \to \mu\gamma)$, and radiative induced Higgs flavor violation decay $h^0 \to \mu\tau$. We show that both diagrams are UV finite. Notice that the total amplitude includes all possible combinations of sleptons in the internal lines, then

$$\mathcal{M}_T = \sum_{j,k} \mathcal{M}_{jk}. \tag{7}$$

3.1. LFV τ decay $BR(\tau \to \mu\gamma)$

We calculate the supersymmetric sfermion-neutralino one-loop contribution to the leptonic flavor violation process $\tau \to \mu + \gamma$ as given in [22], which corresponds to the Feynman diagram given in Fig.1. The experimental bound to the branching ratio for this decay at 90% C.L. [25] is $\mathcal{BR}(\tau^\pm \to \mu^\pm\gamma) < 4.4 \times 10^{-8}$.

The total amplitude is gauge invariant and free of UV divergences as it should be, and can be written in the conventional form

$$\mathcal{M}_T = \bar{u}(p_1) i\sigma^{\mu\nu} k_\nu \epsilon_\mu (E + F\gamma^5) u(p_2) , \tag{8}$$

where the one loop functions E and F contain the sum of the contributions from sleptons $\tilde{l}_{1,2,3,4}$ running inside the loop,

$$E = 5C \sum_{\tilde{l}} E_{\tilde{l}} , \qquad F = -3C \sum_{\tilde{l}} F_{\tilde{l}} , \qquad C = \frac{ieg^2 \tan^2\theta_W \sin\varphi}{2(16\pi)^2(m_\tau^2 - m_\mu^2)}. \tag{9}$$

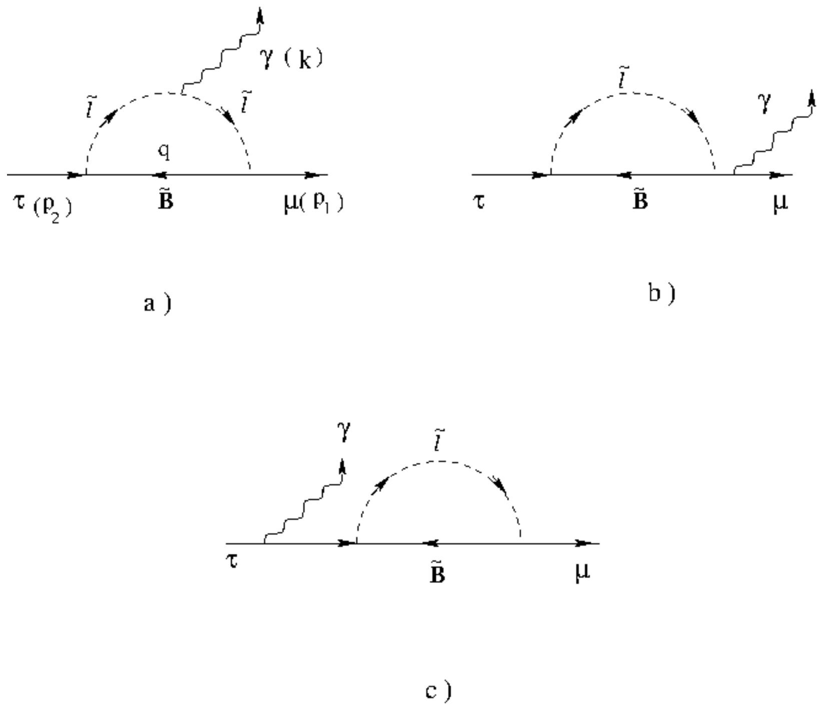

Figure 1. One Loop diagrams in the LFV process $\tau \to \mu\gamma$. The total amplitude is gauge invariant and finite in the UV region.

The functions $E_{\tilde{l}}, F_{\tilde{l}}$ are written in terms of Passarino-Veltman functions and can be evaluated either by LoopTools [26] or by Mathematica using the analytical expressions for $C0$ and $B0$ [27],

$$\begin{aligned}
E_{\tilde{l}} = & \frac{\eta(\tilde{l})}{(m_\tau + m_\mu)} \Big\{ - \Big[1 + 2m_{\tilde{l}}^2 C0(m_\tau^2, m_\mu^2, 0, m_{\tilde{l}}^2, m_{\tilde{B}}^2, m_{\tilde{l}}^2) \Big] (m_\tau^2 - m_\mu^2) \\
& + \frac{(m_{\tilde{l}}^2 - m_{\tilde{B}}^2)}{x} \Big[B0(m_\mu^2, m_{\tilde{B}}^2, m_{\tilde{l}}^2) - B0(0, m_{\tilde{B}}^2, m_{\tilde{l}}^2) - x^2 \Big[B0(m_\tau^2, m_{\tilde{B}}^2, m_{\tilde{l}}^2) - B0(0, m_{\tilde{B}}^2, m_{\tilde{l}}^2) \Big] \Big] \\
& + \Big[B0(m_\tau^2, m_{\tilde{B}}^2, m_{\tilde{l}}^2) - B0(m_\mu^2, m_{\tilde{B}}^2, m_{\tilde{l}}^2) \Big] \Big(m_\tau m_\mu - 2(m_{\tilde{l}}^2 - m_{\tilde{B}}^2) \Big) \Big\} \\
& (-1)^r \frac{8}{5} m_{\tilde{B}} \Big[B0(m_\tau^2, m_{\tilde{B}}^2, m_{\tilde{l}}^2) - B0(m_\mu^2, m_{\tilde{B}}^2, m_{\tilde{l}}^2) \Big] \qquad (10)
\end{aligned}$$

$$\begin{aligned}
F_{\tilde{l}} = & \frac{\eta(\tilde{l})}{(m_\tau - m_\mu)} \Big\{ (m_\tau^2 - m_\mu^2) \Big[1 + 2m_{\tilde{l}}^2 C0(m_\tau^2, m_\mu^2, 0, m_{\tilde{l}}^2, m_{\tilde{B}}^2, m_{\tilde{l}}^2) \Big] \\
& + \frac{(m_{\tilde{l}}^2 - m_{\tilde{B}}^2)}{x} \Big\{ B0(m_\mu^2, m_{\tilde{B}}^2, m_{\tilde{l}}^2) - B0(0, m_{\tilde{B}}^2, m_{\tilde{l}}^2) - x^2 \Big[B0(m_\tau^2, m_{\tilde{B}}^2, m_{\tilde{l}}^2) - B0(0, m_{\tilde{B}}^2, m_{\tilde{l}}^2) \Big] \Big\} \\
& + \Big[B0(m_\tau^2, m_{\tilde{B}}^2, m_{\tilde{l}}^2) - B0(m_\mu^2, m_{\tilde{B}}^2, m_{\tilde{l}}^2) \Big] \Big(m_\tau m_\mu + 2(m_{\tilde{l}}^2 - m_{\tilde{B}}^2) \Big) \Big\} \qquad (11)
\end{aligned}$$

where we have defined the ratio $x = \frac{m_\mu}{m_\tau}$, with possible values of $r = 1, 2$ set as $\mu\tilde{,}\tau_r$ and the $\eta(\tilde{l})$ function as follows: $\eta(\tilde{\tau}_{1,2}) = -1$, $\eta(\tilde{\mu}_{1,2}) = 1$. We see clearly from these two expressions that the loop is finite. The branching ratio of the $\tau \to \mu + \gamma$ decay is given by the familiar expression

$$\mathcal{BR}(\tau \to \mu\gamma) = \frac{(1 - x^2)^3 m_\tau^3}{4\pi\Gamma_\tau} [|E|^2 + |F|^2] \ . \qquad (12)$$

3.2. Higgs flavor violation coupling with sleptons
The Lagrangian which gives the interaction of scalar neutral light Higgs h^0-slepton-slepton is given as

$$\mathcal{L}_{h^0\tilde{l}\tilde{l}} = Q_{\tilde{l}}\left[\tilde{l}_L^*\tilde{l}_L + \tilde{l}_R^*\tilde{l}_R\right]h^0 + G\left[(-\frac{1}{2}+s_w^2)\tilde{l}_L^*\tilde{l}_L - s_w^2\tilde{l}_R^*\tilde{l}_R\right]h^0 + \chi_{\tilde{l}}\left[\tilde{l}_L^*\tilde{l}_R + \tilde{l}_R^*\tilde{l}_L\right] \tag{13}$$

where

$$Q_{\tilde{\mu},\tilde{\tau}} = \frac{g m_{\tilde{\mu},\tilde{\tau}}^2 \sin\alpha}{M_w \cos\beta} \ , \tag{14}$$

$$G = g_z M_z \sin(\alpha+\beta) \ , \tag{15}$$

$$\chi_{\tilde{\mu},\tilde{\tau}} = \frac{g m_{\tilde{\mu},\tilde{\tau}} \sin\alpha}{2M_w cos\beta}(A_{\tilde{\mu},\tilde{\tau}} - \mu\cot\alpha) \ . \tag{16}$$

Then, in the slepton physical states, as rotated by (6), the explicit couplings to the light Higgs boson are given in [28].

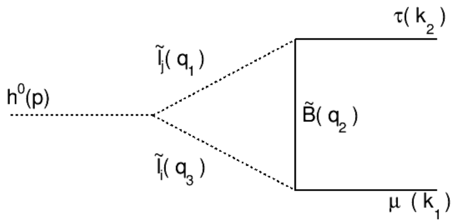

Figure 2. *1-loop SUSY slepton flavor mixing contribution to $h^0 \to \mu\tau$.*

$$\Gamma(h^0 \to \mu\tau) = \sum_{jk} E|\alpha_{jk}|^2\left(D|S_{jk}|^2 + F|P_{jk}|^2\right) \tag{17}$$

S_{jk} is the scalar part and P_{jk} is the pseudoescalar part of the matrix amplitud M_{jk} and the explicit forms given below in table 1 . The parameter α_{jk} is build from all the constants coming from the product of the three couplings $g_{h^0 f_j f_k} g_{\tilde{B} f_j \mu} g_{\tilde{B} f_k \tau}$; and E, D and F are functions of the external particle masses.

The functions in table 1 f^{jk} are functions of the all masses involved, and are given as

$$f^{jk} = \left(m_{h_0}^2 - (m_\mu - m_\tau)^2\right)\left(-m_{\tilde{B}}^2(m_\mu + m_\tau) + m_\tau\left(m_{\tilde{f}j}^2 - m_{h_0}^2 + m_\tau(m_\mu + m_\tau)\right) + m_{\tilde{f}k}^2 m_\mu\right) \tag{18}$$

And we see that the loops are UV finite from the following relations on Passarino-Veltamn functions that appear:

$$F_C^{jk} = \frac{i}{16\pi^2} C0(m_{h^0}^2, m_\mu^2, m_\tau^2, m_{\tilde{f}_k}^2, m_{\tilde{f}_j}^2, m_{\tilde{B}}^2) \tag{19}$$

$\tilde{l}_j\tilde{l}_k$	S^{jk}	P^{jk}
$\tilde{\mu}_1\tilde{\mu}_1$	$-8/A\left[F_B^{11}-F_C^{11}f^{11}\right]$	$6m_{\tilde{B}}F_C^{11}$
$\tilde{\mu}_1\tilde{\mu}_2$	$6m_{\tilde{B}}F_C^{12}$	$8/A\left[F_B^{12}-F_C^{12}f^{12}\right]$
$\tilde{\mu}_1\tilde{\tau}_1$	0	0
$\tilde{\mu}_1\tilde{\tau}_2$	$-8/A\left[F_B^{14}-F_C^{14}f^{14}\right]$	$6m_{\tilde{B}}F_C^{14}$
$\tilde{\mu}_2\tilde{\mu}_1$	$6m_{\tilde{B}}F_C^{21}$	$-8/A\left[F_B^{21}-F_C^{21}f^{21}\right]$
$\tilde{\mu}_2\tilde{\mu}_2$	$8/A\left[F_B^{22}-F_C^{22}f^{22}\right]$	$6m_{\tilde{B}}F_C^{22}$
$\tilde{\mu}_2\tilde{\tau}_1$	$8/A\left[F_B^{23}-F_C^{23}f^{23}\right]$	$6m_{\tilde{B}}F_C^{23}$
$\tilde{\mu}_2\tilde{\tau}_2$	0	0
$\tilde{\tau}_1\tilde{\mu}_1$	0	0
$\tilde{\tau}_1\tilde{\mu}_2$	$8/A\left[F_B^{32}-F_C^{32}f^{32}\right]$	$6m_{\tilde{B}}F_C^{32}$
$\tilde{\tau}_1\tilde{\tau}_1$	$8/A\left[F_B^{33}-F_C^{33}f^{33}\right]$	$6m_{\tilde{B}}F_C^{33}$
$\tilde{\tau}_1\tilde{\tau}_2$	$6m_{\tilde{B}}F_C^{34}$	$-8/A\left[F_B^{34}-F_C^{34}f^{34}\right]$
$\tilde{\tau}_2\tilde{\mu}_1$	$-8/A\left[F_B^{41}-F_C^{41}f^{41}\right]$	$6m_{\tilde{B}}F_C^{41}$
$\tilde{\tau}_2\tilde{\mu}_2$	0	0
$\tilde{\tau}_2\tilde{\tau}_1$	$6m_{\tilde{B}}F_C^{43}$	$8/A\left[F_B^{43}-F_C^{43}f^{43}\right]$
$\tilde{\tau}_2\tilde{\tau}_2$	$-8/A\left[F_B^{44}-F_C^{44}f^{44}\right]$	$6m_{\tilde{B}}F_C^{44}$

Table 1. Explicit form of the scalar and pseudoscalar parts of the matrix amplitud of the loop.

$$
\begin{aligned}
F_B^{jk} = \frac{i}{16\pi^2}&\Bigg\{m_{h^0}^2 m_\mu\left[B0(m_{h^0}^2,m_{\tilde{f}_j}^2,m_{\tilde{f}_k}^2)-B0(m_\mu^2,m_{\tilde{B}}^2,m_{\tilde{f}_j}^2)\right]\Bigg\}\\
&+m_{h^0}^2 m_\tau\left[B0(m_{h^0}^2,m_{\tilde{f}_j}^2,m_{\tilde{f}_k}^2)-B0(m_\tau^2,m_{\tilde{B}}^2,m_{\tilde{f}_k}^2)\right]\\
&m_\mu^3\left[B0(m_{h^0}^2,m_{\tilde{f}_j}^2,m_{\tilde{f}_k}^2)-B0(m_\mu^2,m_{\tilde{B}}^2,m_{\tilde{f}_j}^2)\right]-m_\tau^3\left[B0(m_{h^0}^2,m_{\tilde{f}_j}^2,m_{\tilde{f}_k}^2)-B0(m_\tau^2,m_{\tilde{B}}^2,m_{\tilde{f}_k}^2)\right]\\
&+m_\mu m_\tau^2\left[B0(m_{h^0}^2,m_{\tilde{f}_j}^2,m_{\tilde{f}_k}^2)+B0(m_\mu^2,m_{\tilde{B}}^2,m_{\tilde{f}_j}^2)-2B0(m_\tau^2,m_{\tilde{B}}^2,m_{\tilde{f}_k}^2)\right]\\
&+m_\tau m_\mu^2\left[B0(m_{h^0}^2,m_{\tilde{f}_j}^2,m_{\tilde{f}_k}^2)+B0(m_\tau^2,m_{\tilde{B}}^2,m_{\tilde{f}_k}^2)-2B0(m_\tau^2,m_{\tilde{B}}^2,m_{\tilde{f}_k}^2)\right]
\end{aligned}
\tag{20}
$$

4. Conclusions

In this work we consider a flavor structure on trilinear soft terms, assuming a two family mixing in the sleptons we explore the consequences of this structure in a particular process involving lepton flavor violation for the Higgs boson. We obtain non-degenerate slepton masses for four of the sleptons which are decoupled from the first family and mixed in flavor. We also found that in physical basis two specific couplings of the Higgs boson with sleptons are zero, *i.e.* $g_{h^0\tilde{\mu}_1\tilde{\tau}_1} = g_{h^0\tilde{\mu}_2\tilde{\tau}_2} = 0$.

We obtain the expression for the one-loop radiative correction of the specific process $BR(\tau\to\mu\gamma)$ and $h^0\to\tau\mu$. The expressions we obtain is found to be UV-finite and can be used to restrict the parameter space of the supersymmetric model applied to this process, as it is very restricted by the experimental data. This kind of structure also gives extra contribution to the muon anomalous magnetic moment $g-2$. So a complete exploration of the parameter for all these processes will be a goal for a further work.

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